THE TUNNEL CONSTRUCTION OF THE HUDSON AND MANHATTAN RAILROAD COMPANY.

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The tendency of population in the civilized world, as it increases with advancing years, is toward congregation into great cities instead of a uniform distribution, and this, as is readily understood, is due to the tremendous concentration of manufacturing industries and commerce and the interrelated business brought about and made possible by improvement in the world's transportation facilities.

While the tremendous growth of modern cities is due to transportation facilities, yet the very increase in population and area has created local transportation problems, within the cities, which were not dreamed of only a century ago, even in the great cities of the old world. This increase in the size of the old cities could not be foreseen; so that, instead of their growing in accordance with a preconceived plan, having ample provision for arteries of communication, we have, unfortunately, development without a plan, the newer portions spreading over the surrounding area, merging intervening villages and towns, and creating problems which can only be solved at great expense. Even in the cities of the newer countries, this growth could not have been foreseen or adequate provision made for it.

As an indication of how little this tendency of population to concentrate in the cities could be foreseen, we have only to consult the United States Census to find that at the first census, in 1790, three-tenths per cent. of the population were living in six cities of eight thousand population or over, while in 1900 thirty-three and one-tenth per cent., or about one third of the population, were living in five hundred and forty-five such cities, and that the population of greater New York is now equal to that of the whole of the United States in 1790. During this period the population of the United

States has increased over nineteen times, while that of the area now comprising New York City has increased seventy times.

New York is the heart and center of the second largest aggregation of people in the world, and differing from London, which ranks first, has reached its present position during a comparatively short life. New York was not laid out as a complete city, but has developed by the fusion of scores of villages. Manhattan Island, when it became populated north of Greenwich village, and was mapped on the present plan, was so laid out because at that time it was contemplated that the North and East Rivers, being the main arteries of traffic, needed the greatest number of thoroughfares with the closest intervals, to connect the water fronts. Consequently, the cross-town streets are spaced close together (about 260 foot centers) while the north and south avenues are widely separated. The growth of New York far to the North and East, beyond the East River, has entirely altered the traffic conditions and has produced one of the most difficult conditions in the solution of the present problem. The municipal limits of the Greater City of New York includes, by no means, all of the metropolitan district, which comprises all the suburbs tributary to New York as a place of business, all of which is essentially part of the aggregation of population to be dealt with in the traffic problem. The estimated population of New York City on December 31, 1909, was 4,516,000. The suburbs on Long Island and Westchester County represent 325,000, while the suburban district in New Jersey represents 1,691,000, making a total of 6,527,000 persons.

The last report of the Public Service Commission returns the total passenger transportation in Greater New York in 1908, on the various subway, elevated and surface lines, omitting transfers, as 1,358,000,000 rides. The service in the New Jersey district was 284,000,000 rides. In that year the steam railroads hauled within the same district over 100,000,000 persons, so that the total passenger rides per annum in the city and vicinity of New York amounts to the fabulous total of 1,742,000,000, an amount equal to one ride per annum for each person in the world.

In the Borough of Manhattan this traffic represents over 400 rides per head of population per annum, while in the entire city the movement has grown, by steady progression, from 164 rides per head of population per annum in 1884, to 300 rides in 1908. The advance in this growth has been marked as each improvement in methods of transportation has been introduced, particularly when electric traction succeeded steam, horses and cable, and again when the subways were opened.

Prior to the opening of the various bridges and tunnels, the ferries in New York Harbor carried 208,000,000 persons per annum, of which amount some 120,000,000 crossed the Hudson River.

No other excuse or explanation than these figures is needed for the construction of the various tunnels under the North and East Rivers.

In the cities the main arteries are unduly congested, and many of them are inadequate to provide for the various classes of transportation imposed upon the surface. In some cases the capacity has been increased by construction of elevated railroads, which, while convenient for the passengers and cheap to construct, are a serious impediment to the full use of the surface, are eyesores to behold, and are a nuisance to the health and nerves of the general public. The use of the sub-surface then, is essential to the development of the increased facilities for rapid transit, where the railroad can be out of sight and its operation out of hearing; where it is not affected by climatic conditions, and where the maintenance costs of structure and equipment is minimized.

In our cities the development of subways near the surface, while convenient for public use, introduces very serious questions in relation to sanitation. The first subway built can be carried out by extensive diversion and reconstruction of the sewerage system, but a point must soon be reached where the entire sewerage system must be considered as preëmpting a definite horizontal section upon which no subways may encroach. After that, subways can be laid out with hardly any limit, at greater depths and to almost any nummer, tier upon tier, as necessity demands, in the solid rock foundation underlying our streets.

We are rapidly getting to this point in New York, as is illustrated at Sixth Avenue and Thirty-third Street, New York, where, in addition to the elevated and surface lines, provision is made for a

Broadway Subway near the surface, below that the Hudson and Manhattan Tunnel, below that again the Pennsylvania Tunnels, and for a cross-town line at a level below these.

The Hudson and Manhattan Tunnels are the direct lineal descendants of the original Hudson River Tunnels commenced in 1873. They are developed from the traffic conditions outlined above.

The original undertaking, if it could have been carried to completion at that time, would, unquestionably, have proved unsuccessful in operation. It was then contemplated to build this tunnel from Fifteenth Street, Jersey City, about midway between the Erie and Lackawanna Railroads to a union station at Washington Square, New York, and to transport therein the steam engines and trains of all the railroads terminating on the westerly shore of this river. The method of construction adopted by Colonel Haskins, while feasible for working in the river silt, would never have been adequate to complete the work, and it is only in the past decade that the art of engineering has reached the point of providing the methods for construction and of operation suitable to the completion of this work and to meet the demands of the travelling public, within the scope of modern operation.

In the subject matter following, describing the methods of tunnel construction, the work of the Hudson and Manhattan Railroad tunnels is directly considered, but except in size of structure, and as providing for totally different types of equipment and operation, the matter is in every respect applicable to the work on the Pennsylvania Railroad tunnels, and it may be noted that the ratios of tunnel sizes to weight of equipment are almost the same in the two propositions. The Hudson and Manhattan system comprises four complete tube tunnels under the Hudson River, a belt line connecting the principal steam railroads terminating in Jersey City and Hoboken, and two terminals in New York City—one up-town and one downtown. It is essentially a distributing and collecting terminal in New York for the transportation lines in New Jersey; and a distributing and collecting agent in New Jersey for the people of New York. Its building has involved more varied character of construction than any underground project ever executed, and certainly represents every known type of tunnel construction. The most spectacular portion of the work, but by no means necessarily the most difficult, is the tunnelling under the rivers.

The Hudson Valley is a deep and narrow gorge, having on the west bank the red sandstone formation of the Newark series, and on the east side the micaceous gneiss of New York. For the most part, this valley—the floor of which is some 250 feet below sea level—is filled with silt. This material at the depth of the tunnel sections is a firm substantial clay. Its specific gravity, wet, is about 1.65, dry, about 2.50; weight per cubic yard, wet, about 103 pounds, dry about 156 pounds. Its chemical analysis is as follows:

	Per Cent.
Water	29.50
Silica	47.52
Iron oxide	2.69
Alumina	11.66
Lime	1.88
Magnesia	1.18
Soda	1.80
Potash	1.82
Chlorine	0.30
Sulphuric anhydride	0.11
Carbon dioxide	0.88
Phosphoric acid	0.13
Organic matter	0.53
	100.00

It will flow under pressure, but will stand very considerable pressure. It is impervious to water, though water will convert it rapidly into a demoralized condition. It is ideal material to tunnel in under modern shield methods.

In stating that the work involved all types of tunnel construction, it is to be understood that portions of the work were in solid rock—in certain locations Newark sandstone, and in others gneiss, and later—in part below the waters of the Hudson River, where at times, alongside the American Line Pier, there was a shell of only five feet of rock between the tunnel roof and the river bed—portions in sand and gravel saturated with water, portions in quicksand also saturated, portions in made or filled ground—the most troublesome material to work in—portions in river silt, where, theoretically, there should have existed twelve feet of silt cover and where at times there was actually none at all until clay was dumped to make an artificial cover, and that finally the work was carried on in every combination of these materials. Below the Hudson River, where the deep channel of 65 feet of water flowed, the tubes on both the up-town and down-town systems passed from silt to full rock and from full rock to full sand; consequently the sections at every point continually changed.

The essential factors in all tunnel construction may be summed up as follows: (1) The removal and disposition of the material; (2) the support of roof and sides during construction; (3) the elimination or disposition of water entering the work; (4) the provision of a safe place for workmen engaged on construction; (5) the construction of a permanent lining and waterproofing it.

Carlyle, after disserting on the weakness of man, writes: "Nevertheless he can use tools, can devise tools. . . . Nowhere do we find him without tools, without tools he is nothing, with tools he is all."

In no line of engineering work are the tools more essential than in the modern art of tunnelling. In every type of structure and in every material the proper and efficient tools are the prime factor in the advanced new art of this work.

In rock tunnels the combination of the modern compressed air operated rock drill with fumeless high explosives; in soft ground the use of compressed air, mechanical haulage, electric light and power, steel temporary false works and reinforced concrete or iron plate lining; and for subaqueous work the use of a shield and other mechanical appliances, has to-day converted into an essentially mechanical process what at one time was replenished by brute force. The power plant needed for carrying out such a piece of construction is of tremendous extent. For the Hudson and Manhattan tunnels, for example, and exclusive of the Sixth Avenue subway, the combined power plants aggregate some 13,500 horse power boiler capacity, operating high and low pressure air compressors, electric generators, and hydraulic pumps delivering water to the shields at a pressure of 5,000 pounds per square inch, as well as saw mills and machine shops. Air pressure was maintained continuously from these plants with no break or interruption for support of some part or other of the work under construction, from September, 1902, to June 14, 1909, and during the construction period over 250,000 tons of coal was consumed, while the value of the plant exceeded $750,000.

The plants installed for the Pennsylvania Railroad Tunnel construction were much larger and more valuable than those of the Hudson Company.

The modern method of shield tunnelling is an evolution, and except in the mechanical details and design, is in no respect new.

Referring to the before mentioned essential factors in tunnel construction, the conditions are met by provisions of the tools or means of construction as follows:

1. For the support of the soil, and the elimination of water, and to provide for the safety of the workmen, we carry out the work under air pressure.

2. For the support of the soil, to provide safety for men, for economical and rapid construction, and in certain cases also for the removal of the soil, we install a *hydraulic shield*.

3. For the permanent lining we require material strong enough to stand the external pressures as soon as erected, and therefore a metal *plate lining* is requisite.

4. For putting in place this permanent lining there is installed, either attached to the shield or operating independently, an *erector*.

5. For water-proofing and protecting from corrosion the iron lining, where the same is erected in sand, or gravel, or partially in rock, *cement grout* is pumped into the rear of the lining by a grouting machine.

The use of air pressure was a very early invention. About 1830 Admiral Cochrane, afterwards Lord Dundonald, took out letters patent for use of air pressure applied to caisson or tunnel construction.

The diving bell had been in use at that time quite extensively for laying foundations under water and for carrying on other engineering works. This represents the simplest form of application of compressed air due directly to the water depth, but obviously without the renewal and replenishment of the air. The greatest possible capacity of bell could only, by any possibility, enable workmen to continue work therein for a very short period, and to renew the air the bell had to be brought to the surface. The admiral conceived the idea that if air were pumped into a working chamber it could be applied at a pressure equal to the full head and thereby exclude water; and, going further still, that if such a chamber were connected with the surface or outer air by a tube or other connection and fitted with large valves, it would be feasible for the workmen to freely pass into and out of the working chamber by simple operation of the valves. This simple method he considered as equally applicable to a caisson or tunnel and for the purpose of excluding water. This is all the air lock is today—a large receptacle of sufficient size for cars, buckets or men, fitted with flap doors, one at each end, and opening the same way, that is inwards, against the higher pressure, and connecting the working chamber with the outer air at atmospheric pressure. It is immaterial whether this air lock is fitted vertical, as is usual in caisson work, or horizontal, as commonly applicable to tunnels, the essential condition being that the lock be built into a bulk-head or diaphragm enabling a pressure of air higher than normal atmosphere to be maintained inside the working chamber, which, in tunnel construction, is usually a length of completed tunnel, while in caisson work it is the lower portion, between the air floor or diaphragm and the cutting edge. The "modus operandi" is extremely simple. To enter air pressure, the person enters through the open outer door or valve and closes it behind him. He is then, so to speak, in a room with both doors shut and at atmospheric pressure. He then admits air under pressure until the pressure within the room is equal to that of the working chamber inside, when, obviously, the inner door can be opened and the passage effected. The use of double and triple locks allowing varying stages of pressure are usual in tunnel work, when high pressures of over twenty pounds are used, as increasing the personal safety of men and expediting the operation in the decompression. The honest observance of rigid rules of health makes the the risks to workmen by air pressure almost nil. These are: (1) Selection of men, limiting the age of men who have not been in the habit of working under pressure to, say, not over thirty years; and careful medical examination of every employee for physical and organic condition, and the exclusion of highly strung nervous subjects; (2) the honest coöperation of employer with the medical officer, so that no man is employed who has not been passed as sound; (3) the rule that no man should work when sick; (4) the rule that, while the time interval for compression should be reasonably slow, the all-important thing is to limit the time rate for decompression. This is the reason for the use of varying stages of pressure.

In the tunnel work by the Hudson companies, from 1902 to 1907, there were 40,000 men examined for work under pressure up to 42 pounds above normal. In that time, in the tunnel work (not including caisson construction) only three men lost their lives owing to caisson disease. Work in caisson is in this respect more hazardous than in tunnel, even at the same pressures, owing largely to the small capacity possible within the working chamber and the higher temperatures under which work has to be carried on.

It was before mentioned that the original idea of using air pressure was simply to exclude water. Later, when about 1869 Colonel Haskins conceived the idea of our Hudson tunnels, he also evolved the idea that air pressure balancing the external earth pressure would retain it, neglecting the fact that the elastic properties of air allow it to take any form, and that consequently rigid support to maintain the shape of the chamber is essential to the application of air pressure for balancing earth pressures. This oversight was the direct cause of a great disaster which occurred in the early days of the Hudson River Tunnel. The invention of the "shield" by Sir Marc Isambard Brunel, in 1818, marks the most interesting step in the art. He had been asked if it was possible to build a tunnel under the Neva at St. Petersburg, and working out a scheme, took pattern from nature. The *Toredo navalis* destroys wooden piles by boring holes through them just at the mud line. The worm attaches itself to the wood and then bores the hole as it moves forward, lining its hole with a calcareous shell and discharging the borings through its body. Its body also closes the hole against water coming in; for if the worm penetrates the wood, or admits water, it dies, and obviously, therefore, it is carrying on its boring operations under air pressure equal to the water head.

Brunel's shield comprised a cutting edge and front shell to form the tunnel and hold the sides and roof; the front, or breast, being held by shutters adjustable to the work as excavated. His shield was to be advanced by screw jacks. The modern shield is a great piece of machinery, but in principle is but little different from that of Brunel. The shield is particularly adapted to the construction of a circular tunnel; though roofing shields, simply to support the roof while lining an arch, are not at all uncommon.

Any other form than the circle would be very difficult to use, owing to the trick a shield has of rotating as it advances. The shield structure consists of a drumshell having an internal diameter slightly larger than the external diameter of the finished lining. The front end is shod with very heavy steel castings to form a sharp V-shaped cutting edge protecting and stiffening the shell. The shell is built up of rolled steel plates in two- or three-ply thickness, with all rivets on outside and inside countersunk smooth and no projecting butt straps at joints. This construction gives a smooth external surface to slide through the soil and a smooth flush internal surface in the tail section. The central section of this drum shell is strengthened by a massive girder construction, which forms the main structure of the shield to withstand the pressures and strains. The rear of this girder construction is plated solid and mud-tight, except for doors in each pocket section which can be opened at the control of the workmen, either to admit materials or allow passage for men. This solid plate of the shield is known as the diaphragm. The depth of the girder construction is regulated largely by the length of the hydraulic jacks, which project through the diaphragm and are heeled as near the cutting edge as possible. To provide for the jacks there is constructed within the outer drum shell an annular space, stiffened between each jack by heavy girders connecting the outer shell to the internal jack space shell. The portion of the shield projecting in the rear of the diaphragm, consisting of only a portion of the drum shell (finished flush inside and outside) is known as the "tail." This only serves the function of providing a safe place in the shelter of which to erect the permanent lining, and slides along overlapping the tunnel tube as construction advances.

If the shield is of large size, there are fitted in front sliding tables, advanced in front of the cutting edge of the shield by hydraulic power, for the double purpose of forming platform for men to work upon while drilling, excavating or breasting the upper face, or to shelter the men working below while doing the similar bottom work, and also to push forward against the timbers used to breast up the face, and to hold them in position during the operation.

The machinery with which the shields are equipped consists of numbers of hydraulic jacks fitted at close intervals around the periphery, the jack cases heeled against and pushing close to the cutting edge by admission of water pressure to the jacks, forcing forward the entire structure of the shield by reaction of the rams against the last erected ring of permanent plate lining. The jacks are controlled by an arrangement of valves, so devised that any jack can be operated singly, or any group of jacks can be operated together by one man, from a convenient platform. By applying pressure to either quarter of the shield, the proper direction is given to advance the shield. The doors are very simple, and the design best adapted depends partly on the character of soil in which the shield is being used. In our work nearly every type of door has been fitted, but the simplest and best adapted to the usual condition of use and emergency is the loose slat. A shield is, needless to say, a very massive piece of construction, as the strains put upon it are enormous. One of the Hudson and Manhattan shields complete weighs about 67 net tons, while a Pennsylvania North River shield weighs about 195 net tons. Presuming that work is being carried out in silt under the Hudson River with pneumatic pressure of 30 pounds per square inch and with all the shield doors closed tightly, the shield is pushed through the clay as though one pushed a stick into a heap of dirt. In that case, with sixteen jacks worked under 5,000 pounds hydraulic pressure, there is a total force of 2,500 tons. This, on the Hudson and Manhattan shields, represents a pressure on the soil equivalent to eleven tons per square foot. It is not often that such a pressure as this is necessary to produce penetration with consequent flow and displacement in silt, nor could it be used in any stiffer material without probable damage to the shield. Sand or gravel, which will not flow, must be excavated or removed, and removed in advance of the forcing forward of the shield, or injury will be done to the structure. In Hudson River silt the process is very rapid, the complete cycle of operation involved in pushing this shield, cleaning up the silt which leaks through the door joints, placing and erecting a complete ring of plates for lining, bolting up and being ready for the next cycle, requiring only thirty-seven minutes, and in this way as much as seventy-two feet of finished tunnel has been erected in a single day.

In the design of a shield there have been numerous so-called refinements introduced, some patented, some tested and discarded; but in our own experience, the greater simplicity the greater service, and any addition to such a machine which is not necessary it is better without. For example, working in sand or gravel, or when the face consists in part of rock and in part of silt or sand, the entire face of soil has to be excavated, and as this is done the breast must be retained from caving or falling in. This is usually done by skilled men placing boards, well and properly braced by struts, through the shield doors back to the completed tunnel, so that they are independent of the movement of the shield when it is next shoved ahead. The addition to the shield of an elaborate mechanically operated system of shuttering, like a glorified edition of Brunel's idea, is no advantage in time nor labor, but enormously increased cost to construct and additional trouble to maintain.

The most difficult combination to deal with in shield tunnelling is a partial face of rock overlaid by silt or wet sand. This construction was first met with and successfully overcome in the East River Gas Tunnel in New York. In this case the soft ground overhead must be excavated and the exposed face securely supported by timber while the rock underlying is drilled and blasted. This work, carried out in air pressure, necessitates very small charges of dynamite and is very tedious and expensive.

One of our shields with which the east-bound up-town tunnel was constructed from under the Hudson River through Morton Street and Church Street and into 6th Avenue as far north as 12th

Street, travelled a total distance of 4,525 feet, of which amount 2,075 feet was constructed with rock over the partial cross-section of the tunnel, and overlaid with wet sand.

During the progress of this shield and for the purpose of blasting and removing the rock, there were exploded 26,000 sticks of dynamite in front of the cutting edge, causing very great damage to the structure of the shield, so that at the time it arrived at 12th Street and 5th Avenue, the shield was in such condition that it was with considerable difficulty that the tunnel lining could even be erected.

As the shield advances, the permanent lining must be erected in the rear. In Brunel's day brickwork was used, and it has recently been used to some extent, but even with the use of quick setting Portland cement neither brickwork nor concrete is successful for subaqueous work, as the materials cannot reach any strength, in the time during which it is feasible to leave the shield, before advancing it again after construction of a ring. Structural iron, imbedded in concrete at the points where jacks react, has been tried without satisfaction, and the use of wood as a temporary lining, to be backed up after advance of the shield by brick or concrete, while satisfactory for small tunnels, is never likely to be much used for any large sized tubes as needed for railroad tunnels. It is essential, for any tube tunnel construction with a shield, to have a permanent lining which can be erected as the shield advances and rapidly put in place, and which, as soon as erected, is strong enough to take all permanent stresses and to permit of the reaction of the jacks of the shields. A metal lining is the only solution of this problem. Cast iron or cast steel has almost exclusively been used, as the forming of the segments is so accurate, the joints are the least in number, and the material is such as to give the longest life with the least depreciation. If an internal concrete lining is afterwards used, then undoubtedly a satisfactory structural steel lining could be designed, but probably with no economy in cost of construction. We have used this to a small extent for experimental purposes. For any such metal lining, the complete ring has to be erected from within the tail of the shield, which is only a couple of inches larger inside than the external size of the finished tube.

Consequently all the plates cannot be made with radial joints, and a key has to be employed which is inverted from the ordinary keystone form, so that it can be placed in position from within the arch instead of from without. The usual length of the key is commonly equal to the distance center to center of the bolts in the circumferential joints, although often made very narrow like a wedge. The rings used in the Hudson tunnels were two feet long face to face, which means that every ring erected represents two feet of finished tunnel. The rings used in the Pennsylvania tunnels are 30 inches long. The rings are bolted together at close intervals at the circumferential joints by heavy steel bolts, and the segments making up a complete ring, by bolts in each longitudinal joint. The number of segments or plates going to make up the ring depends on convenience of handling, the usual limitation being for a length not exceeding six feet. For the Hudson and Manhattan tubes this worked out to nine segments, all having the same length, and a key. The segments weigh approximately 1,200 pounds apiece, and the placing of these at any point in the circle would be difficult and slow without a machine erector. This is one of the most human-like machines possible. It reproduces the human arm as exactly as possible. The erector (singular or plural, for in a big-sized tunnel more than one erector may be used simultaneously) is a machine either attached to the diaphragm of the shield or entirely independent. We have used both types and have invariably found the independent type most elastic and convenient in operation. This machine may be operated entirely by hydraulic power, or, as is very usual, by hydraulic power for the in-and-out movement of the arm and by pneumatic engine or electric motor for the revolving movement. The end of the arm is fitted with a simple attachment, representing a hand, which grips a plate segment in the middle so that it will balance. The plate is first dumped from a tunnel construction car on to the bottom portion of the tail of the shield already pushed forward and ready to allow the erection of a ring; then the arm of the erector hangs vertically and is attached to the plate; the arm recedes by operation of the hydraulic ram lifting the plate a few inches, then the arm, which is pivoted about its center and partially counterbalanced for the weight of the plate, revolves until the plate reaches the position in the circle which it is permanently to occupy, when the arm moves forward, shoving the plate into position, and the bolts are inserted and secured. Plate after plate is erected, until finally the insertion of the key completes a ring, when the shield is again advanced.

By subdivision of all bolt holes absolutely uniformly around the pitch circle in the circumferential joint, it is feasible to shift the position of the key at every ring and thereby stagger the longitudinal joints, increasing materially the rigidity and strength of the tunnels.

For subaqueous tunnelling in silt or sand, this method of the tube construction is essential to safety to employees as well as to safe and certain construction of the work itself; and with it and with competent labor employed, subject to certain limitations as to depth, it is difficult to imagine any condition which would prevent successful execution of a piece of work.

In the tunnel work of the Hudson & Manhattan Railroad there is a greater length constructed under the land than under the water, although every portion, except the Sixth Avenue Subway, north of 12th Street, is below tide level. A portion of this work has been in solid rock, though most of it is built through sand and gravel formation. Under these conditions the use of a shield has not at all times been necessary, and a very large portion of the tunnels could, for economic reasons, be advantageously built with concrete lining, under pressure but without the shield. The function of the engineer is to determine when this can properly be done, and when it can, the saving by substitution of concrete for metal lining is very great, though the metal lining can be more easily made absolutely water tight in wet ground than a concrete lining.

A considerable amount of tunnel construction in solid rock has been carried on with a shield, using iron lining, on account of the likelihood of troubles arising, owing to fissures or thin cover in the roof, which, in the absence of the shield for protection and support, might be troublesome to execute.

The whole art of tunnel construction in soft ground by any process depends on the proper support of every hole exacavated, and as excavated. A small hole in any kind of soil may be safely made without immediate support; but as soon as it is enlarged, the soil will cave in, unless given support to hold the material *in situ.* This is the purpose of the shield, and it is also the theory upon which tunnels are constructed by the ordinary mining methods. With the latter method air pressure has always been used to keep the water back. Narrow advance headings are driven corresponding to each side wall, and about at the springing line, in which timber mud sills are laid, acting as foundation for the temporary steel sets which support the roof. Then as the soil in the upper portion of the tunnel between side bearings is removed, length by length, these steel centers are put in place to carry the wooden planks known as "laggings," which are placed tight together to give continuous solid support to the external soil. Then the lower portion of the excavation is removed and posts with lagging put in below the sills, to hold the roof and sides until the permanent lining of reinforced concrete can be put in place.

In these subaqueous tunnel operations, as the influx of water is the "bugaboo" of the "sand hog," for the restraint of which air pressure is employed, so the greatest danger arising from the use of air pressure is the "blow out." Safety in such operations is dependent on the maintenance of a nice balance between the air pressure within and the water pressure without the tunnel. In the case of a diving bell or caisson, the exact amount of air pressure necessary to balance the column of water extending vertically from the rim of the diving bell or cutting edge of the caisson to the surface of the water, can be automatically determined. If too much pressure is used, the excess will escape under the cutting edge, and if not enough, the water will rise in the working chamber above the cutting edge. In the case of a tunnel, however, no such exact determination can be had, as the bottom of the tunnel, being deeper, requires a greater pressure to exclude the water than the top, and if this pressure is used, there will not be enough water pressure at the top to prevent the air from escaping, and if only enough is maintained to balance the water at the top, the bottom will be flooded. Fortunately the overlying material, to a greater or less extent, dependent on its character, permits of the maintenance of a greater pressure than that due to the hydrostatic head, so that the tunnel engineer exercises his judgment and fixes on a pressure that will not escape through this material and will exclude as much water from the bottom of the tunnel as possible. Some escape of air occurs in nearly all materials, excepting the most impervious, and this escaping air, if pressure is too great, blows the particles of materials away and enlarges the passages until they become so large that the air escapes faster than it can be supplied, when the air pressure drops and an inrush of water occurs. This is what is meant by a "blow-out."

For any railroad tunnel, in order to minimize the gradient of approaches, the grade is necessarily established at the least depth feasible below the bed of the river or below the surface; and where, as in the Hudson River, the water is sixty-five or seventy feet deep, and man cannot, with safety, work under air pressure exceeding forty-five pounds per square inch, which represents a hydrostatic depth of salt water of one hundred and two feet, it is obvious that the amount of cover over the roof of a tunnel and below the bed of the river must be very small. If the soil is in any degree porous, and pressure is allowed to drop, there is a grave liability of the ground becoming "demoralized" by infiltration of water, and if pressure is then raised to check the inflow, it sometimes happens that the cover of soil cannot withstand the increase, and the roof is blown off or a big hole blown out, and water then comes in in large quantities, often beyond control, so as to flood the tunnel works within the air locks.

The instinct of an unskilled foreman is usually to raise pressure in case of a leak commencing. If nothing happens it may be a good thing to have done, but an expert will usually lower the pressure in this case, putting up with the nuisance and difficulty of having a good deal of water in his tunnel and thereby allowing the greater external pressure to squeeze what soil exists into the pockets of the shield and thereby choke the leak. There is far greater skill and caution needed to raise air pressure than to lower it, in case of any leakage occurring. In the event of a "blow" it may be small, in which case it can be stopped from inside by stuffing up into the hole bags of sawdust, hay, balls of clay, and in fact anything handy and available to fill a hole. Usually this prompt treatment will relieve the condition so as to allow the shield to be pushed past the blow hole. Sometimes, however, the hole will increase in size, often quite suddenly, and get beyond control, in which case all doors in the shield are closed up and the men are removed before the tunnel fills with water. In one famous incident which occurred in one of the East River tunnels, a small blow had developed and a man was in front of the shield stuffing bags of hay in the hole, when the pressure sucked the bag into the hole suddenly, and the man, failing to let it go quickly enough, was carried, hanging to his bag, through the ground into the waters of the river, when he rose to the surface and was picked up alive by a passing boat. When the condition is reached that the tunnel is completely flooded, the steps to be taken to recover it must be from outside. Soundings are then taken very carefully and accurately to determine the locality and extent of the blow hole in the bed of the river. A large quantity, usually several hundred cubic yards of good stiff silt or clay, is loaded in a dumping scow, and at "slack water" the scow is towed into position over the hole, being located by instrumental observation from triangulation points on shore, and on signal from the two observers of simultaneous correct position the scow is instantly dumped. Soundings are then again taken to ascertain if the hole is completely filled, and if not, scow after scow is dumped at the same point. Following that, air is then pumped into the tunnel, forcing the water out through the blow pipes; as the pressure is gradually raised it soon becomes evident whether or not the hole is plugged. In the construction work on the up-town tunnels of Hudson and Manhattan, there occurred fully a dozen blows, necessitating dumping clay, although only in four or five cases was the tunnel flooded. In one of these most persistent cases, which had been occasioned by gross incompetence on the part of the night foreman, who advanced the shield with too many doors open, dumping was carried on until half the tunnel was full of silt, and then the leak was only stopped by spreading a sail sheet over the hole and dumping additional material on top. When the tunnel was recovered and cleaned out, the sail covered the door opening. The increased skill and experience attained by the workman before the down-town tunnels were built was shown in the fact that only two blow-outs occurred, in neither of which cases was the tunnel lost, and each of these was due to striking fissures in the rock formation close in shore. It is not unusual to provide against the chances of "blow outs" by artificially increasing the cover over a tunnel by dumping good stiff clay as a thick blanket over the tube location before the work is executed, and ultimately dredging and removing this clay. This method was carried out, to a very large extent, in the East River tunnels of the Pennsylvania Railroad.

One important item of work in connection with subaqueous tunnelling is that of "grouting." The purpose of this is two fold: (1) To fill the small annular space due to the shield's being slightly larger than the tunnel lining, as well as any other voids or cavities in the rear of the working face, and render the exterior soil solid, thereby giving more perfect support to the lining; (2) to waterproof and protect the material of the lining itself. Grouting consists in mixing hydraulic cement with an excessive quantity of water, so as to make it almost liquid, and then pumping it, either with a force pump or grout machine, through holes provided in the lining, into any spaces or interstices in the surrounding material. Cement mixed neat or in a very rich mortar with sand, and particularly if it has originally been mixed with an excess of water, when set up and thoroughly crystallized, makes an exceedingly impervious material. In the iron lining plates, there are usually provided one hole to each segment of plate, screw-tapped to permit the insertion of a piece of iron pipe having a hose attachment connected to the grout machine. This machine was invented by Greathead, and consists of a small tank in which blades or paddles are rapidly revolved on a shaft by an air engine or motor. To the tank is fitted an extension box with a flap door opening inwards, through which the change of cement (usually one barrel at a time) with the water needed to make slurry of it, can be admitted. The only other attachments are a large pipe for admission of air at high pressure, and a discharge pipe fitted with a cock. The operation is simple. Having put into the tank the cement and water, the paddles are run until they are thoroughly mixed, the flap door closed, and air admitted at high pressure into the tank. As soon as the discharge valve is opened, the mixed grout is forced through the hose to its position outside the lining. The penetrating power of grout under high pressure is remarkable, and it will follow the easiest channel. It is not desirable to use grout where the exterior soil is silt, as the pressure of water softens the silt into mud, preventing the setting of cement and demoralizing the silt in proximity to the lining. Further, it is not required in that character of soil to fill the voids, as clay will flow sufficiently to fill all voids itself. In sandy soil, either with metal or concrete lining, grout is always used, and usually in the case of tunnel built in rock. Along the streets of New York we have repeatedly traced dead connections with sewers by finding grout follow open pipes into houses and fill the cellars. Lifting the tracks of railroads or lifting asphalt pavements of streets sixty feet overhead of the tunnel, have not by any means been unknown occurrences, and the bodily raising of a standing building has been done on one occasion. By filling all voids promptly as the shield progresses, when tunnelling under land, the settlement of soil can be reduced to an extremely small amount, so much so that short lengths of tunnel have been driven under occupied dwellings without the tenants being aware of the fact.

The subject would hardly be complete without a brief reference to the construction of portions of the tunnel work by caisson methods. The general underlying principles of caisson construction are similar to those of shield tunnel work—progress being made vertically instead of horizontally—but for a great many years the use of caissons has been almost exclusively for the construction of piers for bridges, or where solid support is necessary for building foundations.

In locating the tunnels for the Hudson and Manhattan system, where the north and south line connecting the steam railway terminals on the New Jersey side intersect the up-town pair of river tubes, a complicated problem existed as to how to connect these lines, so as to enable the trains crossing the river to run southerly to the Pennsylvania and Erie Railroad terminals, northerly to the Lackawanna terminal, and from the latter point to the down-town river tubes. To enable these train movements to be executed necessitated what in railway parlance is known as a "Y" junction. In case the tracks for trains moving in opposite directions had been placed side by side at the same elevation, as is usual, dangerous grade crossings would have been established at three points of juncture, which would have impaired safe and rapid operation. The idea was therefore conceived of placing the tracks for trains moving in opposite directions close together, but one above the other, so that at points of intersection they would be on different levels. At the three junction points where each single tunnel diverged, it was necessary to build a switch chamber or section of tunnel, having the width of a single tunnel at one end and gradually widening until sufficient width was obtained for the construction of the two diverging tubes; and owing to the separation of grades in the tubes, these chambers needed to be double decked. As the shield is only adapted to the construction of a fixed size and form of tunnel, it could not be used, and some other method had to be devised.

To construct these chambers by underground mining methods involved very serious hazards, due to their great size and the unstable character of the material at the roof level. On the other hand, to dig an open pit from the surface was not feasible, owing to the great depth and danger of infiltration of water from the river nearby into the excavation. The method finally adopted was to build these sections of tunnels on the surface as monoliths of concrete reinforced with steel, and then to sink them as pneumatic caissons to their final position. They were built complete with the exception of the bottom of the lower chamber, which was left open so as to serve as a working chamber for the excavators. The material excavated was passed out through shafts extending through the upper chamber, and thence through an air lock to the surface, whence it was removed or dumped on the descending caisson in order to give additional weight to cause the caisson to sink by overcoming the friction of the surrounding material on the sides. When each caisson had been sunk to the proper level, they were completed by an inverted concrete arch closing the bottom and sealing the connecting tunnels joined to them. In some cases the shields were driven to the caissons, then rolled through and continued on the opposite end. Each of these caissons took about three months to sink, and the largest weighed twelve thousand tons. During the construction and sinking, by arrangement with the railroad companies, traffic was suspended on the railroad track immediately above the caissons.

The conditions were very much worse, however, in the case of the construction of the approaches to the Church Street Terminal Station under Cortlandt and Fulton Streets, where the arrangement of switches desired was such that the tunnels could not be built by shields and the caisson method was used. In this case the business had to be continued on the surface of these streets at all times, from beginning to end of the construction work, and further, all sewer pipes, steam pipes, electric conduits, etc., had to be in use and operation throughout the entire period of construction. The difficulty, due to adjacent buildings not having foundations which extended below the cellars, made necessary other methods than those adopted in Jersey City. The cofferdam enclosing the entire area of the buildings had already been sunk, by a series of caissons, to bed rock around the entire area, and these approaches had to be constructed contiguous with the exterior of the cofferdam taking in practically the entire width of Cortlandt Street and Fulton Street, building line to building line.

In this case an absolutely new departure in caisson construction was adopted, which involved sinking boxes, forming short sections of tunnel, with solid sides, the same being built up as the caissons descended. These boxes had to be sunk entirely from below the level of the street, and their sides were built up five feet at a time as they sank, special types of air locks being necessary to enable the work to be carried on in this manner. These caissons, too, contrary to the usual custom, were sunk without roofs, that is to say, the permanent floor of the tunnel was designed as the roof of the working chamber, and the sides of the box built up of reinforced concrete, but the ends with steel plates reinforced with pin-connected truss girders. These boxes were sunk by loading with pig iron in order to obtain the necessary weight, and when they had reached their permanent position timber struts were put in to take the external pressures on the side walls, pending the construction of the roof. When the various caissons had been sunk, one against the other, until the whole strip of tunnel had been completed, the removable steel ends of the boxes were taken out and the permanent roof put on to the side walls.

The difficulties of doing this work under the conditions may be appreciated when it is understood that, in Cortlandt Street alone, the 6th and 9th Avenue Elevated Roads had to be supported, and not only a public sewer in each street had to be maintained, but also a twenty-four inch steam pressure main (under 90 pounds of steam pressure all the time) as well as a bank of electric conduits which carried about seven thousand wires, comprising every telephone and telegraph wire in the down-town section going out of New York City.

The tunnels under these streets could undoubtedly have been built by the tunnel methods indicated in the earlier part of this paper, possibly at some saving in cost, but any such methods would have involved such risks of damage to buildings and adjacent properties that such a saving would have been far more than offset by damages in case a building was wrecked. By this method the construction of these difficult portions of tunnels, where junctions between the different lines were involved, could be carried on with almost absolute safety, and as the results proved, there was practically no injury to any properties adjacent or immediately above the construction itself.

The work which has recently been carried out in New York City, the construction not only of the tunnels of the Hudson and Manhattan Railroad, but also those of the Pennsylvania Railroad, have developed almost every possible combination of conditions which could by any possibility arise in tunnel construction, and the enormous magnitude of work carried on in the last six or seven years has been done with practically no disasters of any kind. These methods described have brought the modern construction of tunnels down to almost an exact science. The hazards and dangers are infinitely less than in the case of bridge construction, and tunnels are applicable in many cases where bridges are not.

In addition to this, the different tunnels permit very much greater elasticity in the development of transportation facilities than the bridges do, and traffic can be more economically and better distributed by developing underground routes than by construction of immense bridges which, on account of the lateral strength and rigidity, must be built on an enormous scale, whereas tunnels can be constructed on any lines, wherever they will give the greatest facilities for distribution of the travelling public.

New York City, and in fact all of our great cities, are absolutely in their infancy in respect to the tunnel for transportation. There is practically no limit to the development of this line of work as the necessities arise and as traffic demands, and we have reached in New York City a point where the possible construction of tunnels can hardly, by any possibility, keep pace with the growth and development of the population and with the necessities for their transportation.

In respect to the rivers, the future, unquestionably, has within sight construction of highway tunnels between New York and New Jersey on the lines of the Blackwall under the Thames in London or similar tunnels under the Clyde at Glasgow, forming underground extensions of existing street thoroughfares; and the object of this presentation of the subject is to give an accurate idea of the principles underlying the construction of such arteries of transportation.